Lattice QCD for Nuclear Physics

1. Lattice QCD infrastructure: people and software
2. Hadronic Parity Violation (PV): I=2 NN PV Amplitude
3. Neutrinoless Double Beta-Decay ($0\nu\beta\beta$)
4. Nucleon Matrix Elements for Fundamental Symmetry Tests

Tight-knit team

red = postdoc
blue = grad student

Lattice QCD Team

LBL/UCB: David Brantley, Chia Cheng (Jason) Chang, W. Haxton, T. Kurth (NERSC), Ken McElvain, Henry Monge Camacho, Amy Nicholson, AWL

LLNL: Evan Berkowitz, Enrico Rinaldi, Pavlos Vranas

Liverpool/Plymouth: Nicolas Garron

JLab: Balint Jóo

CCNY/RIKEN: Brian Tiburzi

NVIDIA: Kate Clark

Computational Scientists

LBL: Fernando Perez, Abhinav Sarje, Sam Williams

LBL (seeking $): Pieter Ghysels, Khaled Ibrahim

SciDAC
Scientific Discovery through Advanced Computing

NERSC

U.S. DEPARTMENT OF ENERGY
INCITE
LEADERSHIP COMPUTING

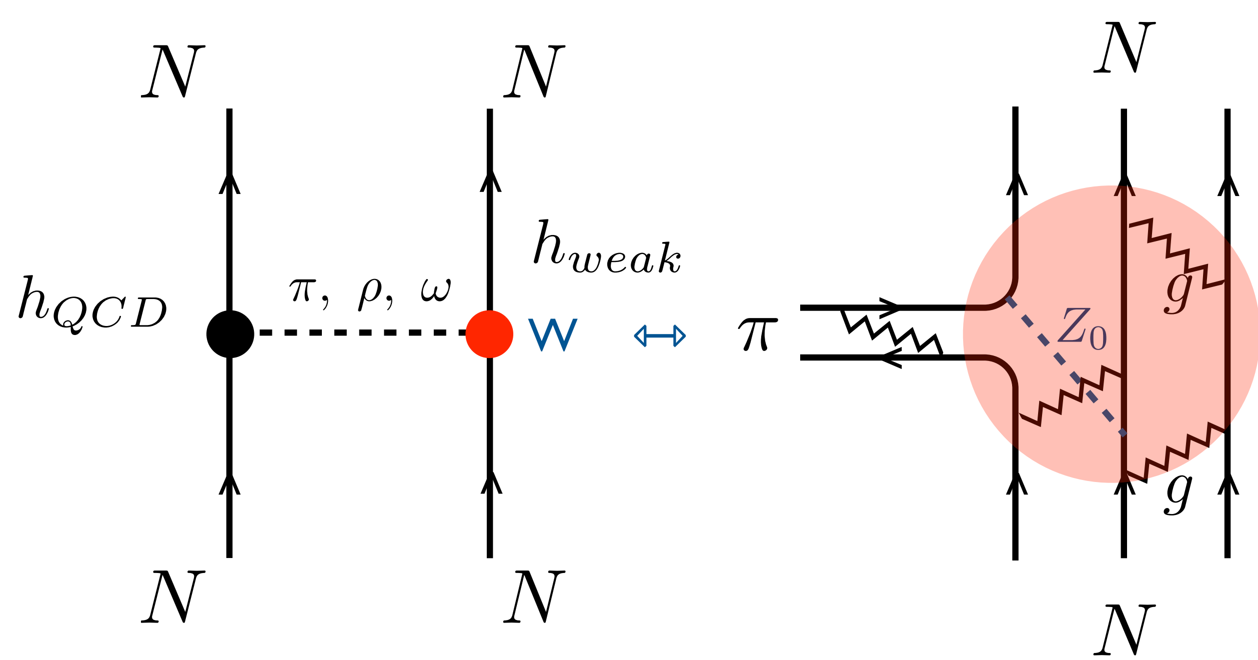
OLCF
Oak Ridge Leadership Computing Facility

Lattice QCD (LQCD) Software

- Our main software, **latscat**, was initially developed by Thorsten Kurth (now @ NERSC). Evan Berkowitz, Enrico Rinaldi and AWL are now co-developers with Thorsten consulting regularly
- We work closely with Kate Clark (NVIDIA) who develops **QUDA** (GPU library) and continues to optimize software for our projects (Titan/OLCF)
- We work closely with Balint Joo (principal developer of USQCD libraries) who continues to optimize and add support for routines we use
- We work closely with Abhinav Sarje (LBL CRD through CalLat SciDAC3) and Ken McElvain (20+ yr software engineer turned UC Berkeley physics grad student) on significant performance optimizations, O(50-100%)
- We have implemented a **NERSC database** to share numerical results amongst ourselves and ultimately, to share our raw LQCD results and our analysis results (the physics) publicly with easy open access to interested physicists
- We are seeking funding for partial support of LBL Computer Scientist/Applied Math scientists who are familiar with exascale development and LQCD to develop next-generation LQCD code for NP on (near-)exascale computers

Hadronic Parity Violation (HPV)

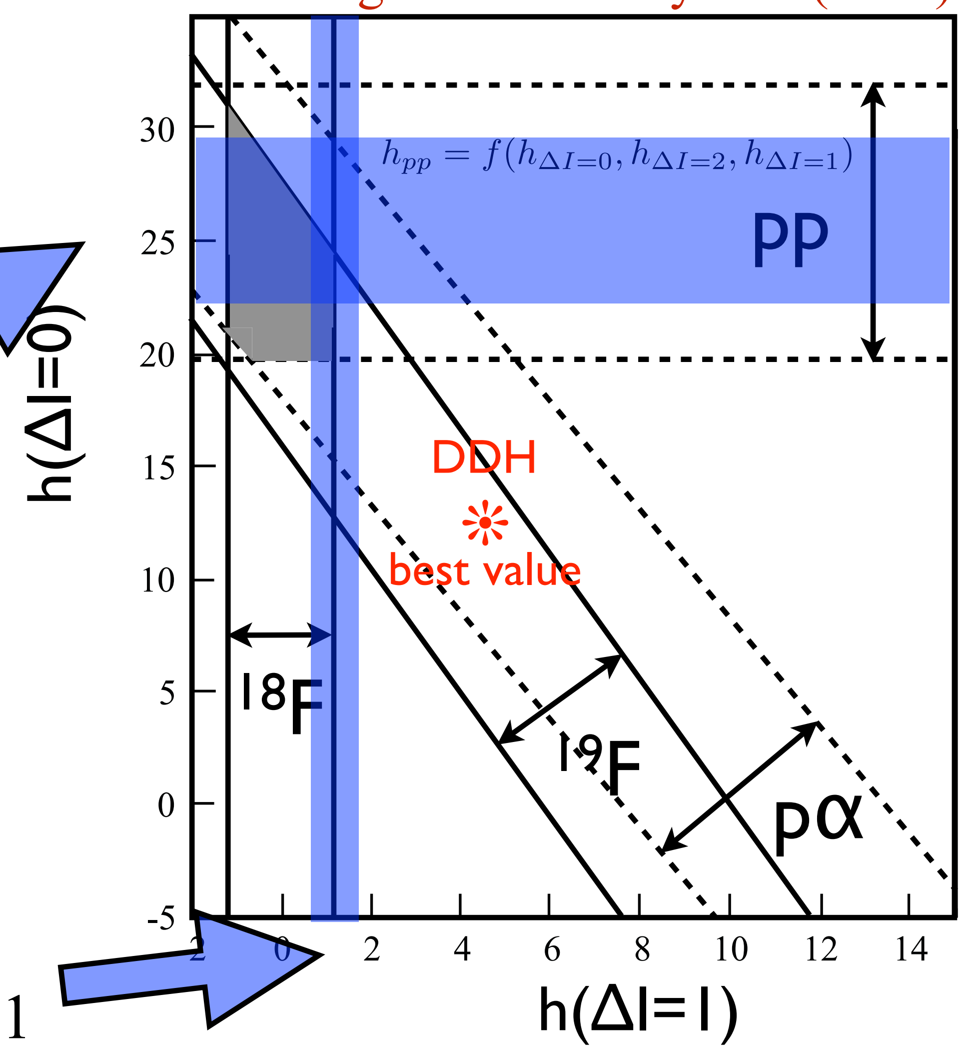
- The first CalLat lattice QCD project planned was to compute the Isospin=2 Hadronic Parity Violating Amplitude between 2 Nucleons



potential impact of a future calculation of

$$h^2_\rho$$

Haxton & Holstein: Prog.Part.Nucl.Phys. 71 (2013)



first LQCD calculation of $h_{\pi NN}$:

L=2.5 f a=0.123f m_π= 389 MeV

systematic approximations

J. Wasem Phys. Rev. C85 (2012) 022501

Hadronic Parity Violation (HPV)

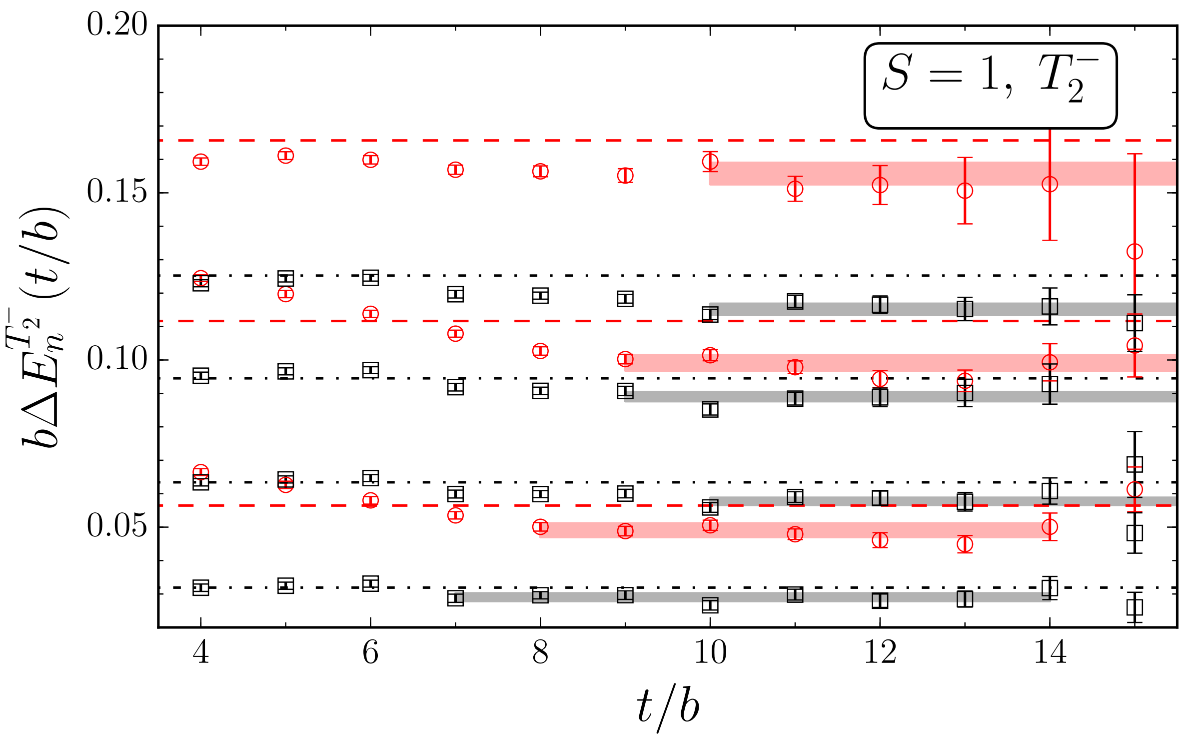
- We needed to develop new technology to compute higher partial wave NN scattering phase shifts (S,P,D,F), displaced two-nucleon interpolating fields $\mathbf{N^\dagger(t_0, x_0)\, N^\dagger(t_0, x_0{+}r_0)\, |0\rangle}$

First LQCD calculation of NN P, D (,F) waves

arXiv:1508.00886 $(m_\pi \simeq 800\ \mathrm{MeV})$

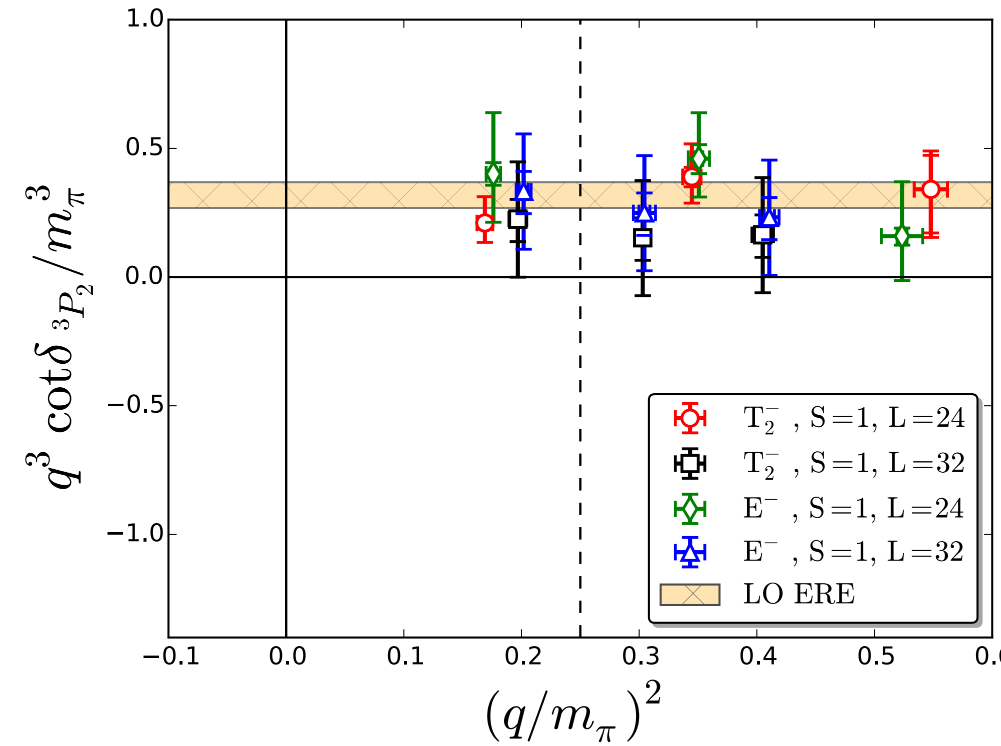
Example: $^3P_2$ - elastic wave

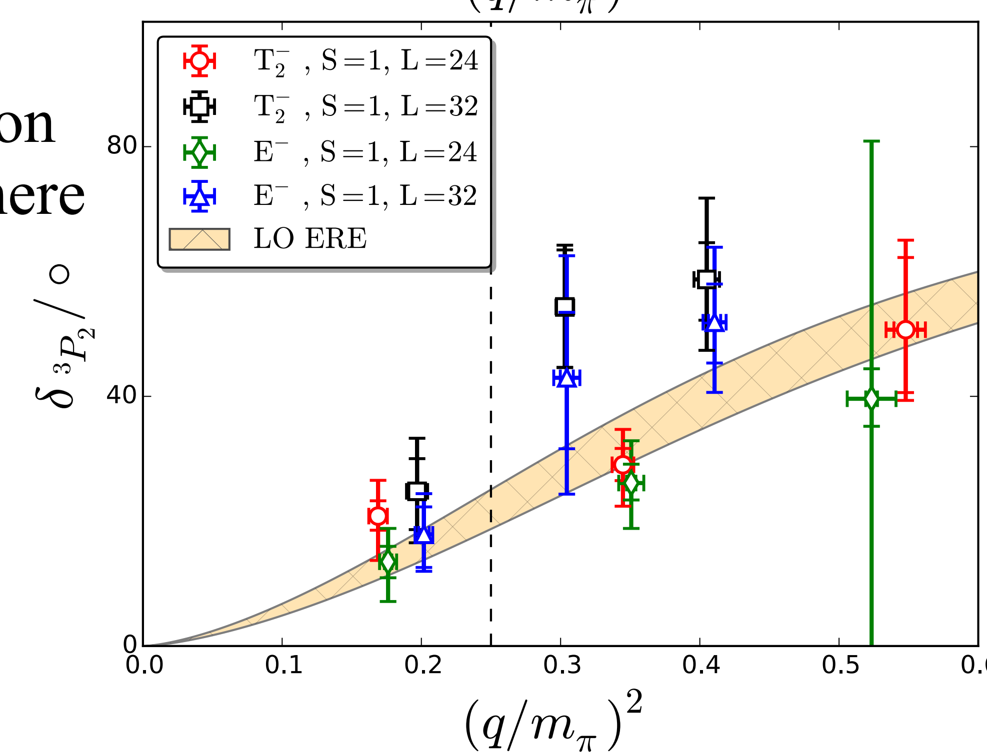
Lattice QCD calculation of NN energy levels



Lüscher Function

cube → sphere

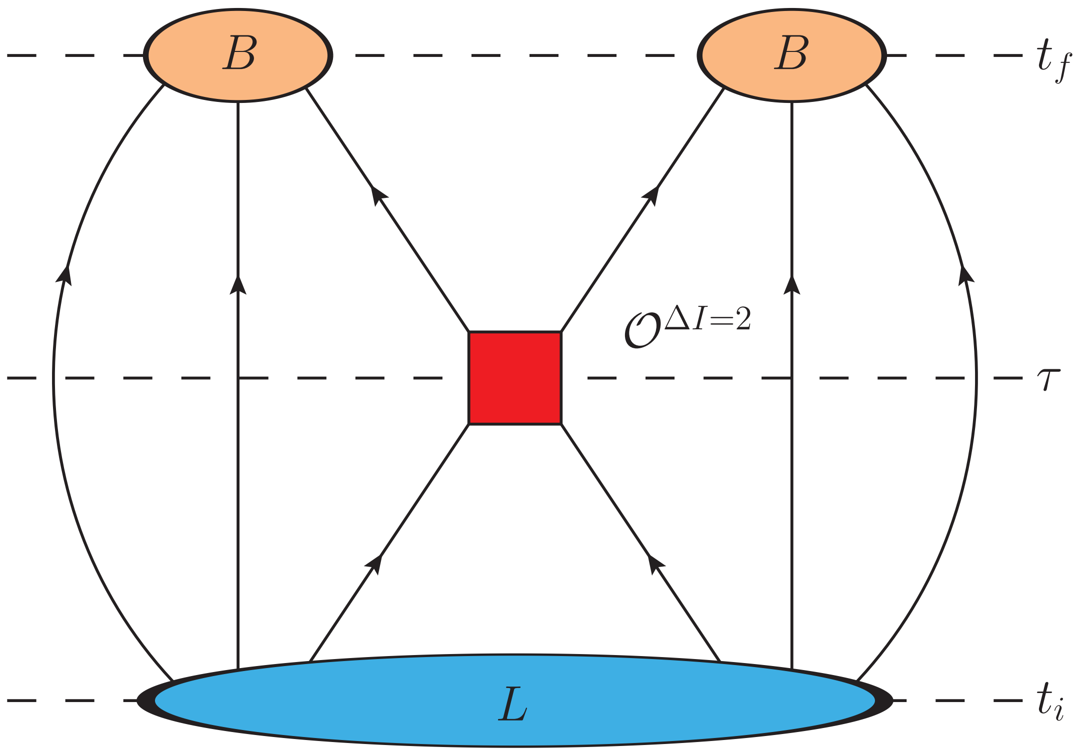




See poster by Amy Nicholson

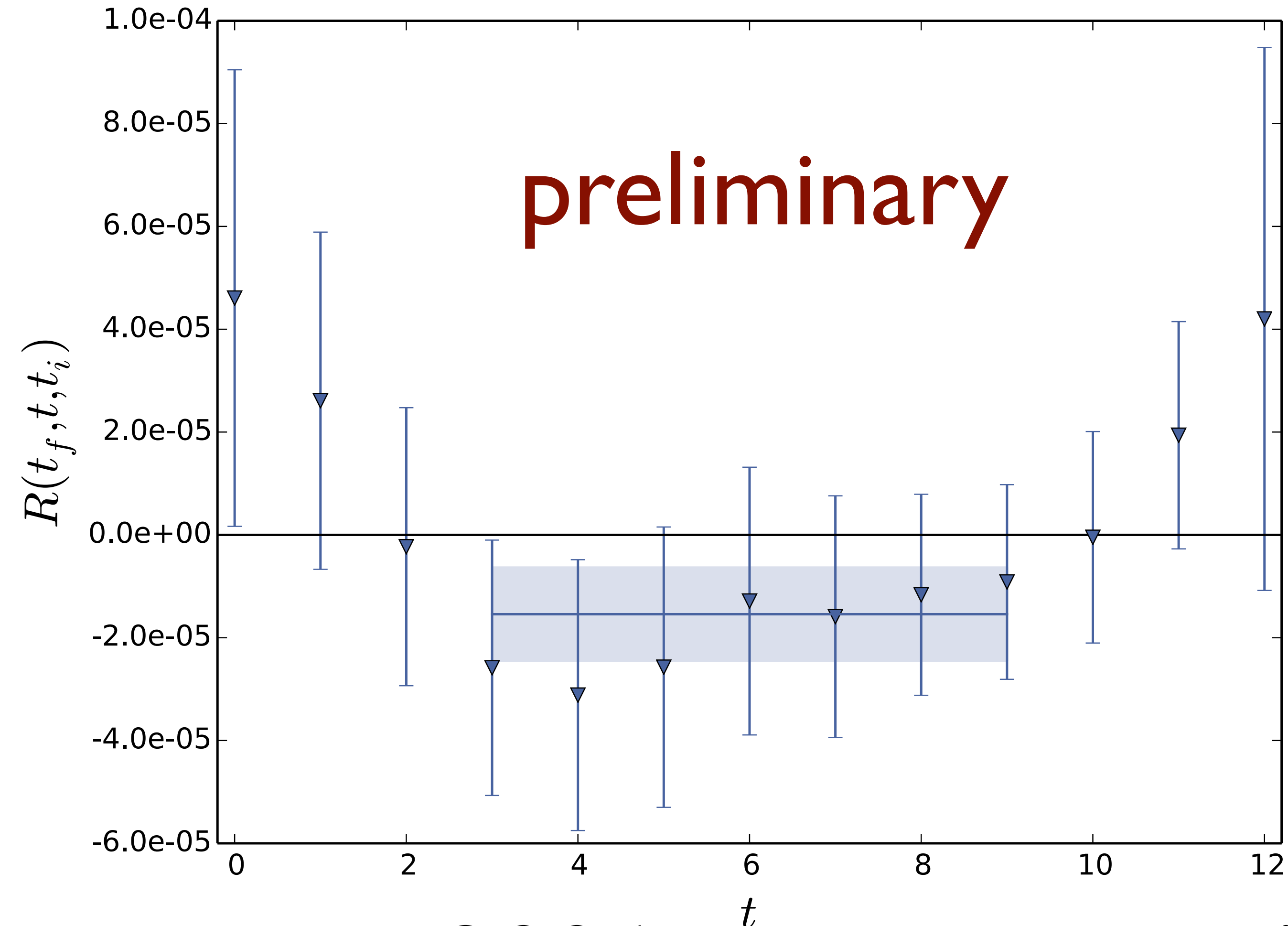
Hadronic Parity Violation (HPV)

P



S

'bare' lattice matrix element



only 200 'measurements'

$$\langle pp(^3P_1)|\mathcal{O}^{\Delta I=2}|pp(^1S_0)\rangle_{V=\infty} = LL\left(\delta_{^1S_0}, \frac{\partial \delta_{^1S_0}}{\partial E}, \delta_{^3P_1}, \frac{\partial \delta_{^3P_1}}{\partial E}\right)\langle pp(^3P_1)|\mathcal{O}^{\Delta I=2}|pp(^1S_0)\rangle_{V=L^3}$$

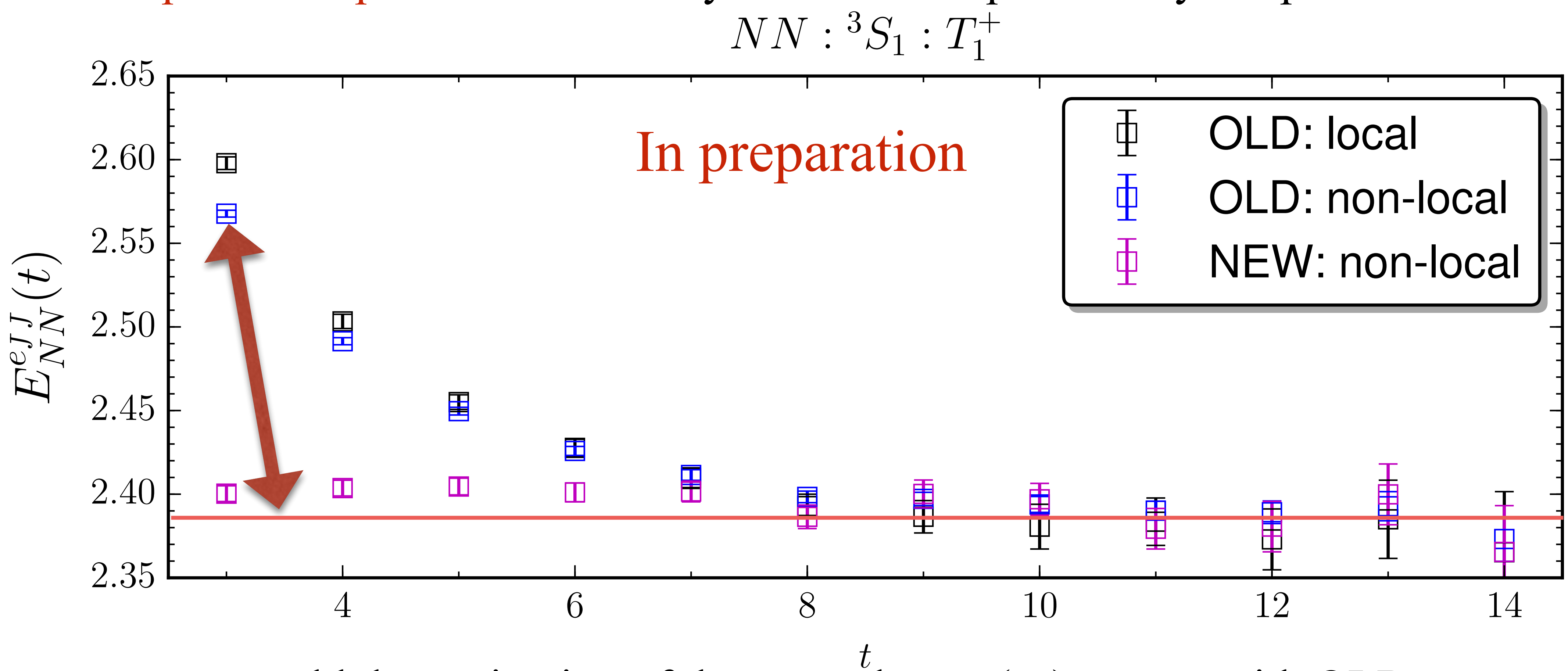
Known Lellouch-Lüscher (LL) function

Raúl Briceño et al

Most significant systematic/challenge for HPV is our determination of good 2-nucleon operators.

Further Improved NN Operators

- We have developed new operators which may allow for "exponentially" improved results.



≃ our old determination of the ground state (gs) energy with OLD operators

= deviation from gs plateau is driven by excited state contamination

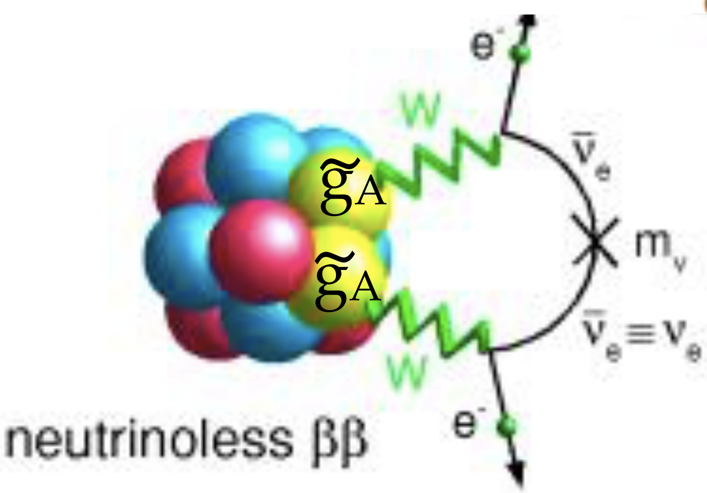
NEW: non-local = our new strategy - the excited state contamination of the two-nucleon correlation function has been significantly reduced. This will allow analysis beginning earlier in time where the stochastic noise is ~ exponentially smaller

OLD: non-local = our recently developed displaced two-nucleon interpolating fields (see previous slides) $\mathbf{N^\dagger(t_0, x_0)\, N^\dagger(t_0, x_0+r_0)\, |0>}$

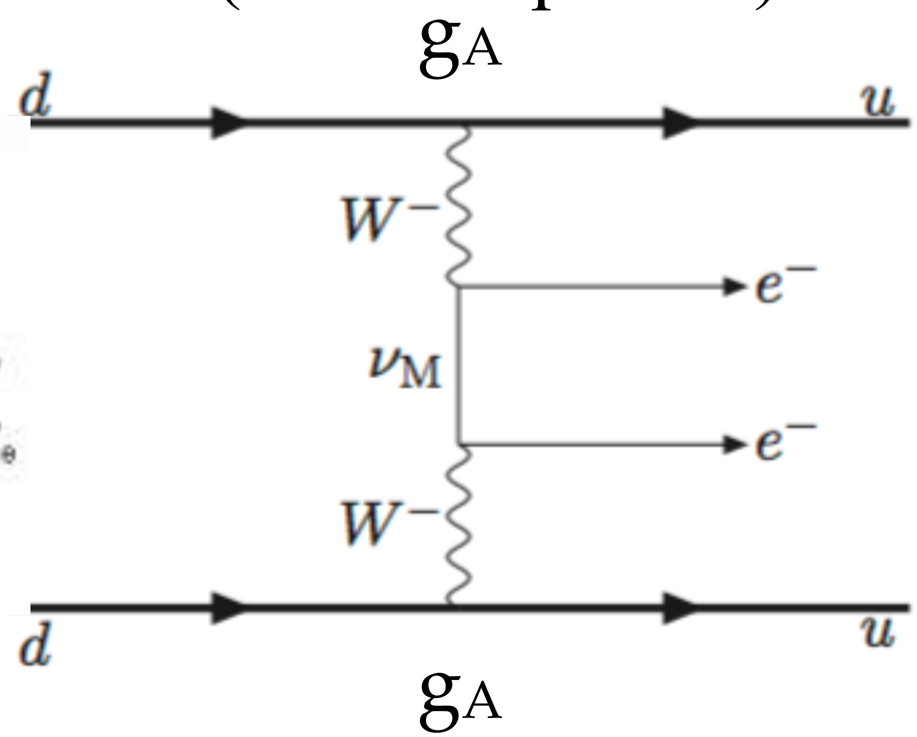
OLD: local = two-nucleon interpolating operators from the same space-time location - the strategy used by most other groups, $\mathbf{N^\dagger(t_0, x_0)\, N^\dagger(t_0, x_0)\, |0>}$

Neutrinoless Double Beta-Decay

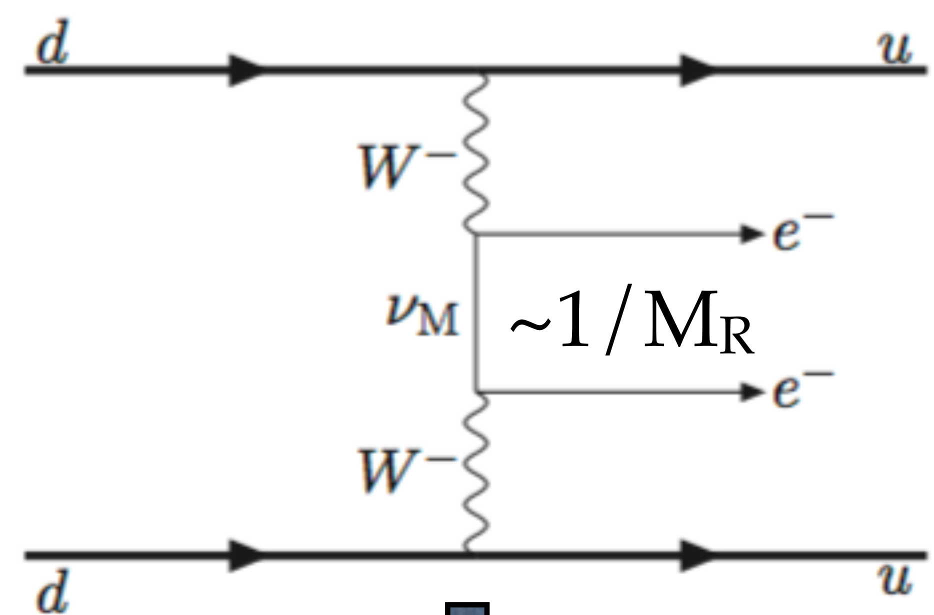
Neutrinoless Double Beta-Decay

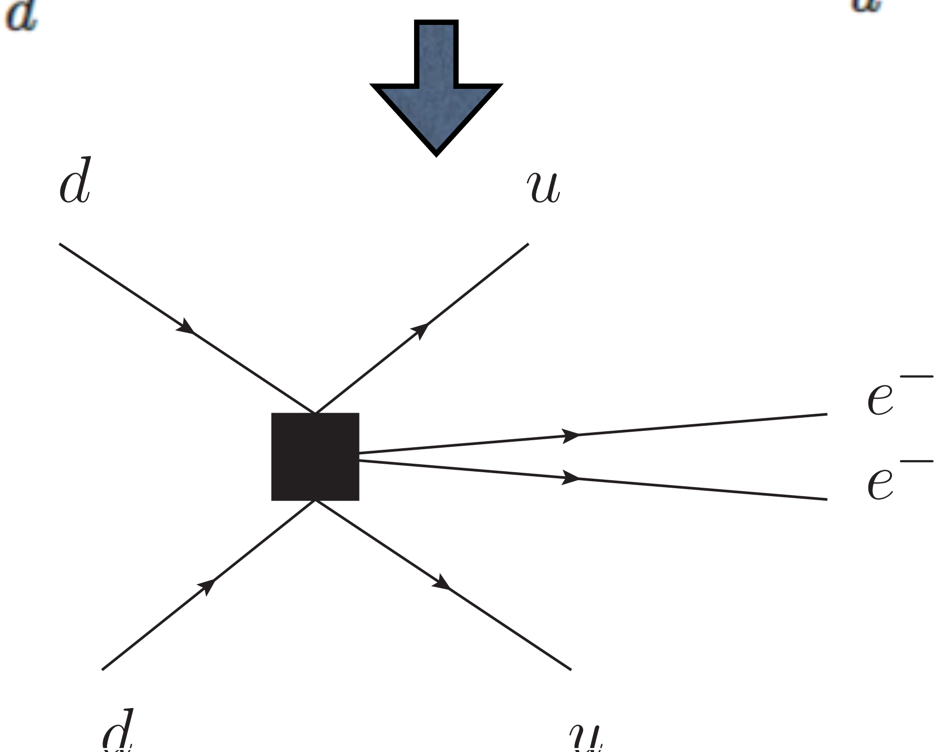


long-range contribution
(standard picture)



short-range contribution
possibly equally/more important





Long Range: lattice QCD can help understand "quenching" of g_A in a nucleus

Short Range: lattice QCD is the ONLY theoretical tool we have to understand these contributions with quantified uncertainties

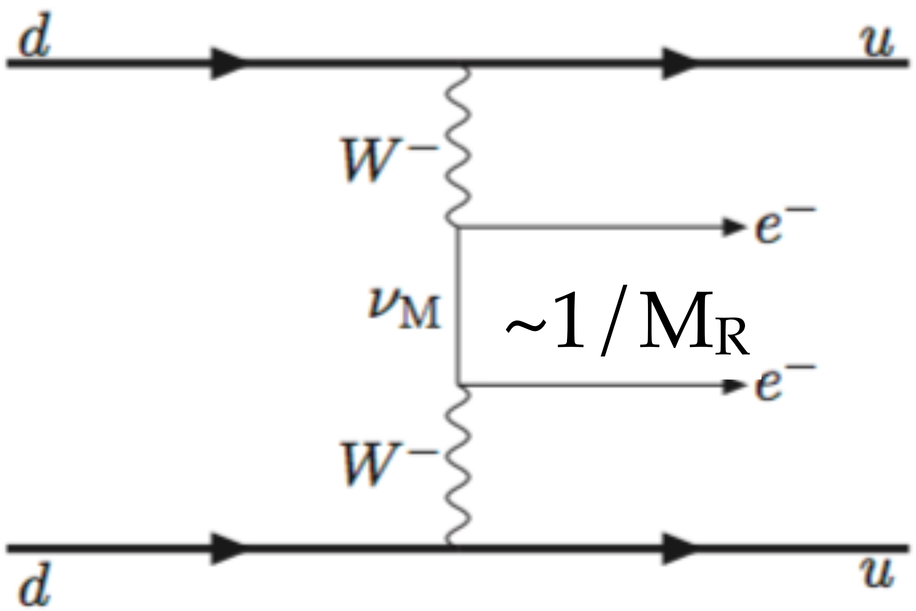
Lattice QCD: compute 2-nucleon matrix elements to determine unknown couplings/transition rates

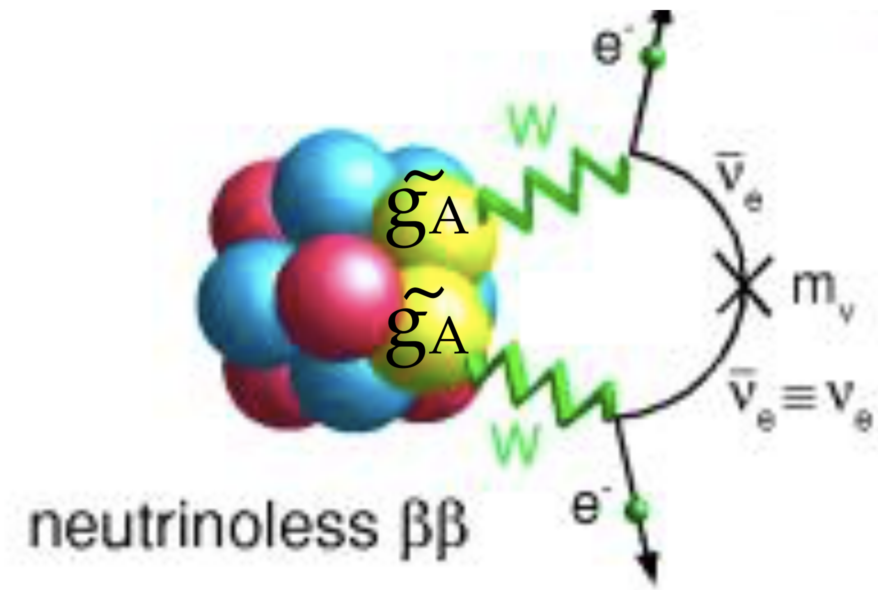
Many Body Nuclear Effective Theory: take lattice QCD results as input and compute transition rate in nucleus (Haxton, others)

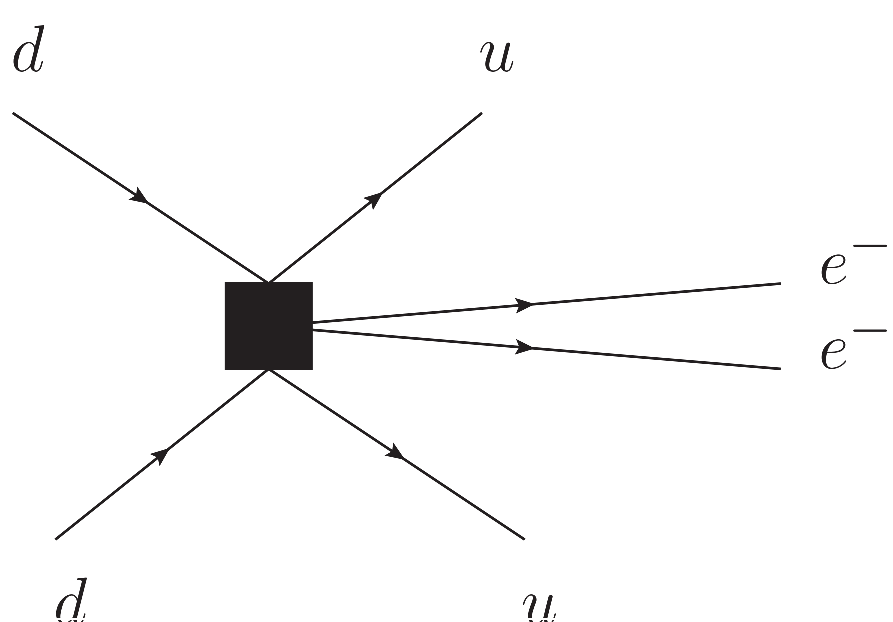
In this review, focus on short-range contributions

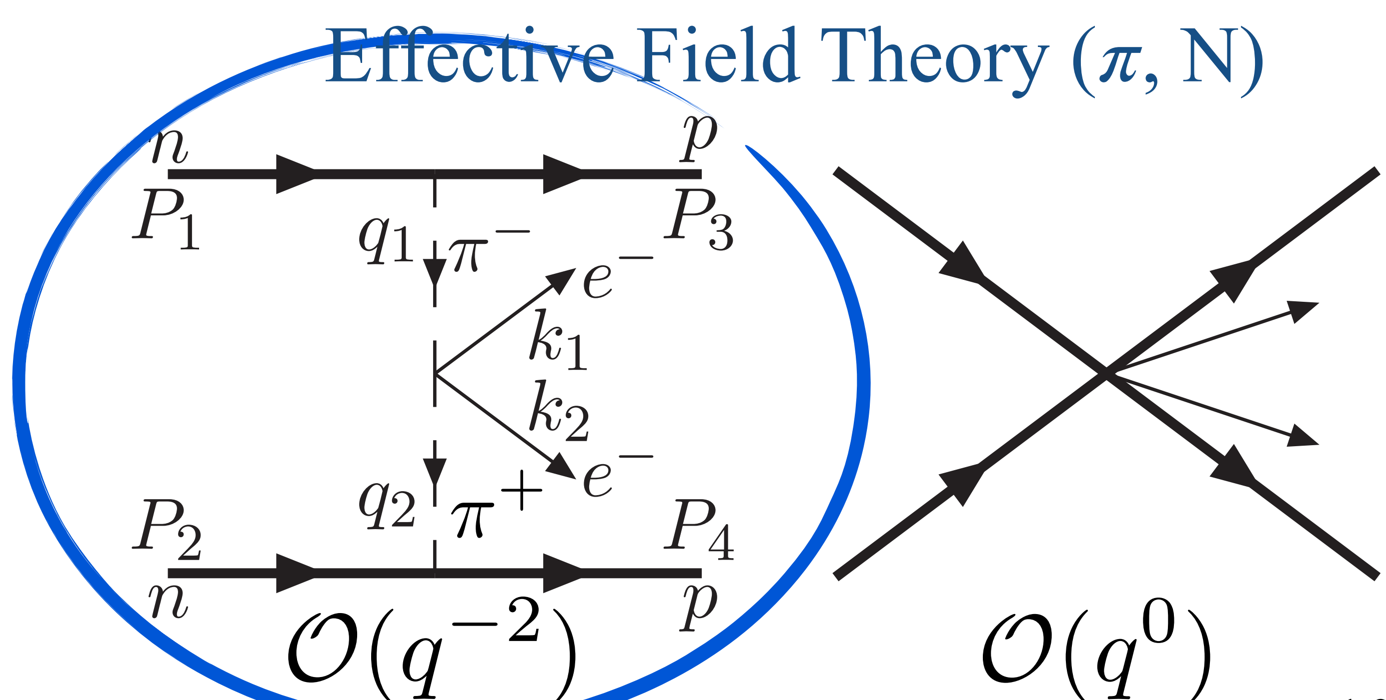
Neutrinoless Double Beta-Decay

Short-range contribution: probe for heavy physics



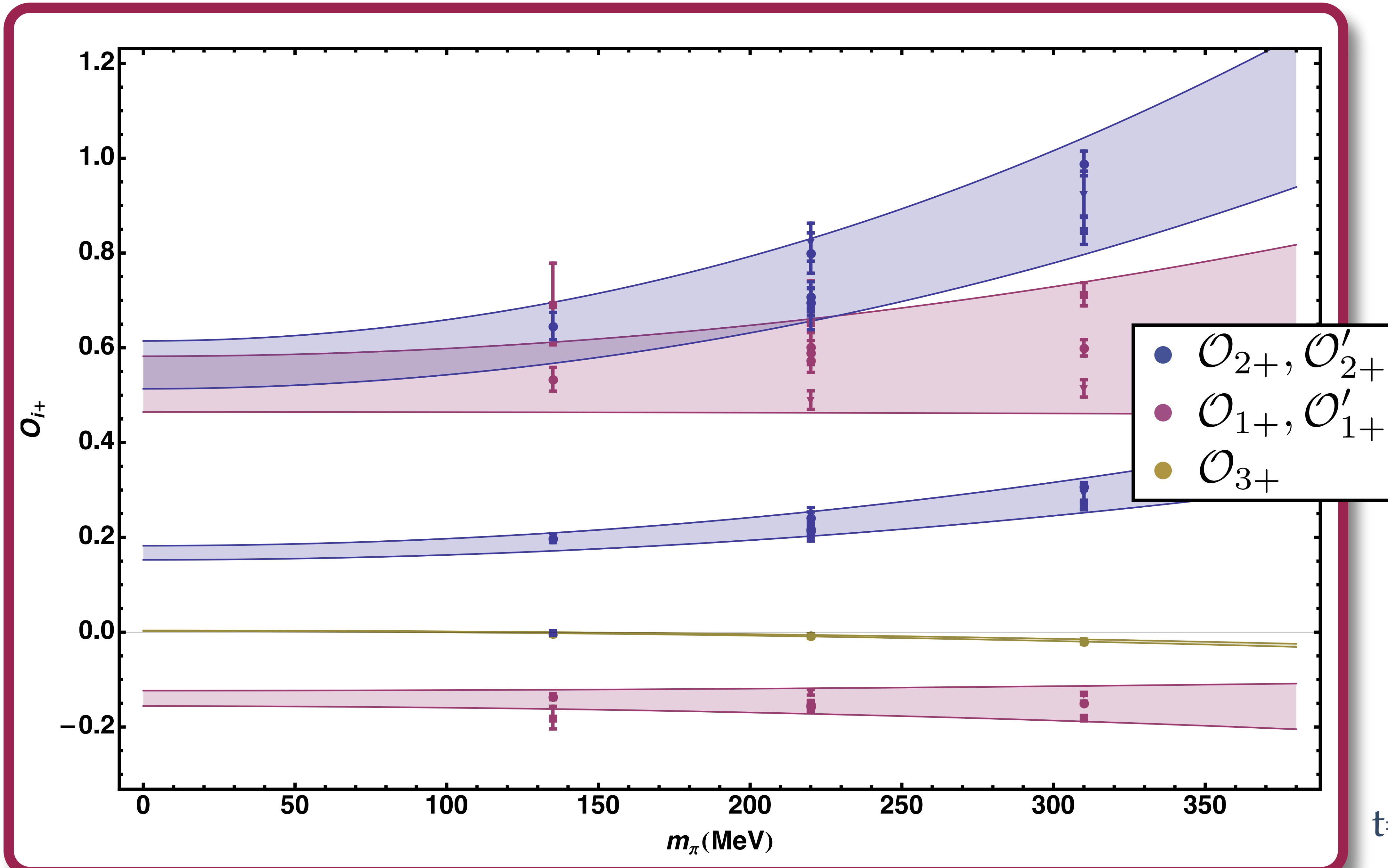


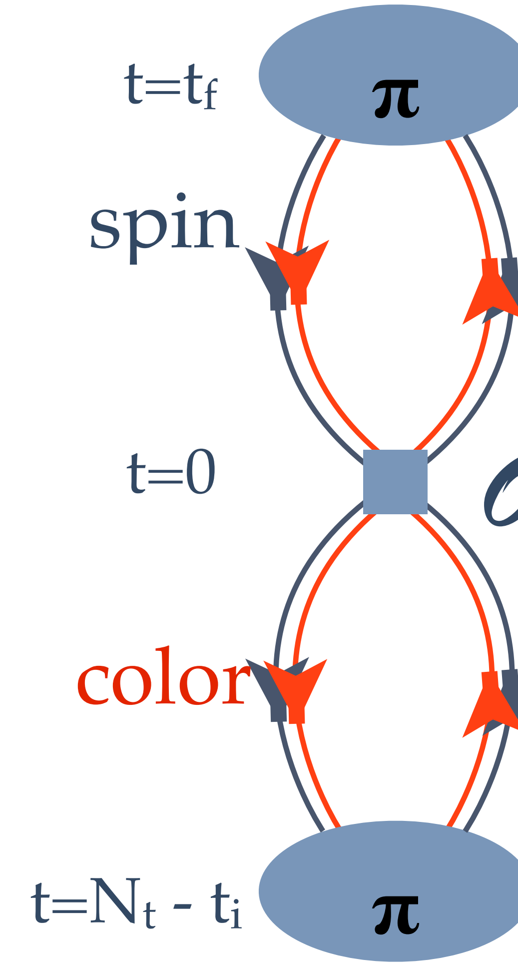


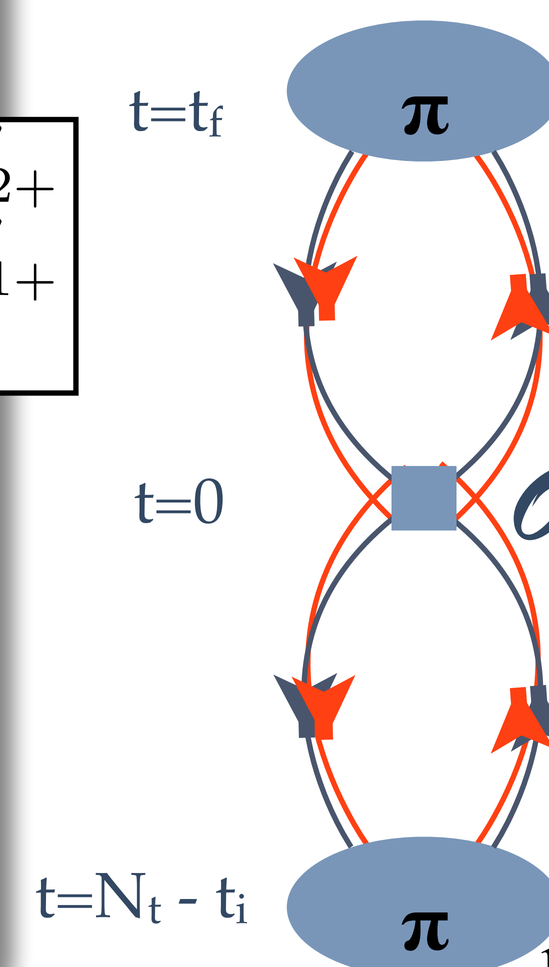


We have performed the first, AND COMPLETE lattice QCD calculation of the $\pi^- \rightarrow \pi^+$ transition amplitude which is expected to dominate the 0νββ rate in the case of short distance physics

- physical pion mass
- continuum and infinite volume limits
- still need renormalization (doing now)
- expected publication within 2 months
- result given to many-body nuclear theory to compute rate





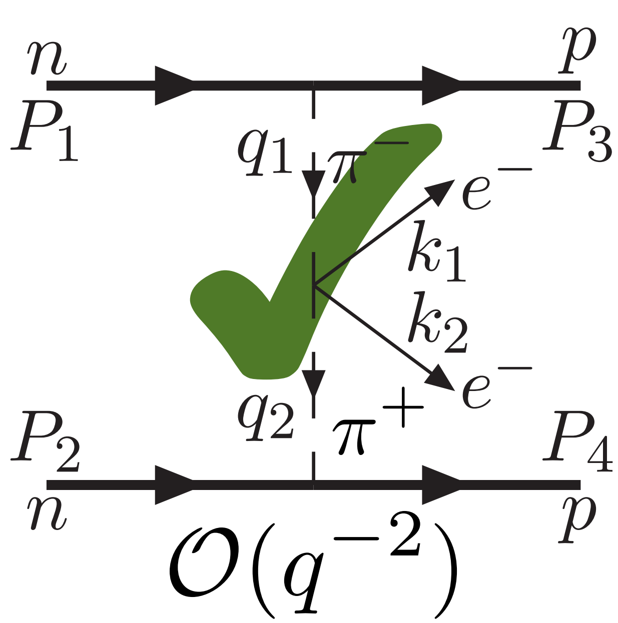


Neutrinoless Double Beta-Decay

Short-distance Contact operators

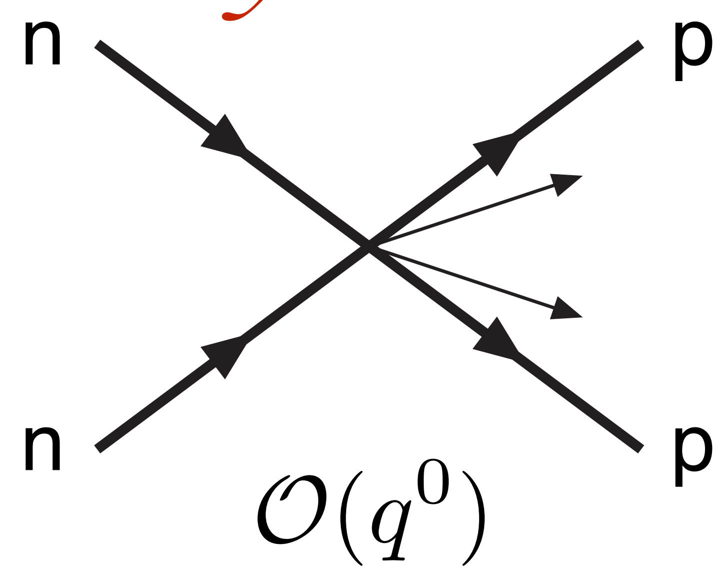
- LO almost complete!
  - dominant contribution to $0\nu\beta\beta$ from short-range contributions
  - need renormalization

- nn → pp contact operators
  next step: similar to two-N hadronic parity violation



$$V_{nn\to pp}(q_1, q_2)$$

Stay Tuned!



Nucleon Matrix Elements & Fundamental Symmetries

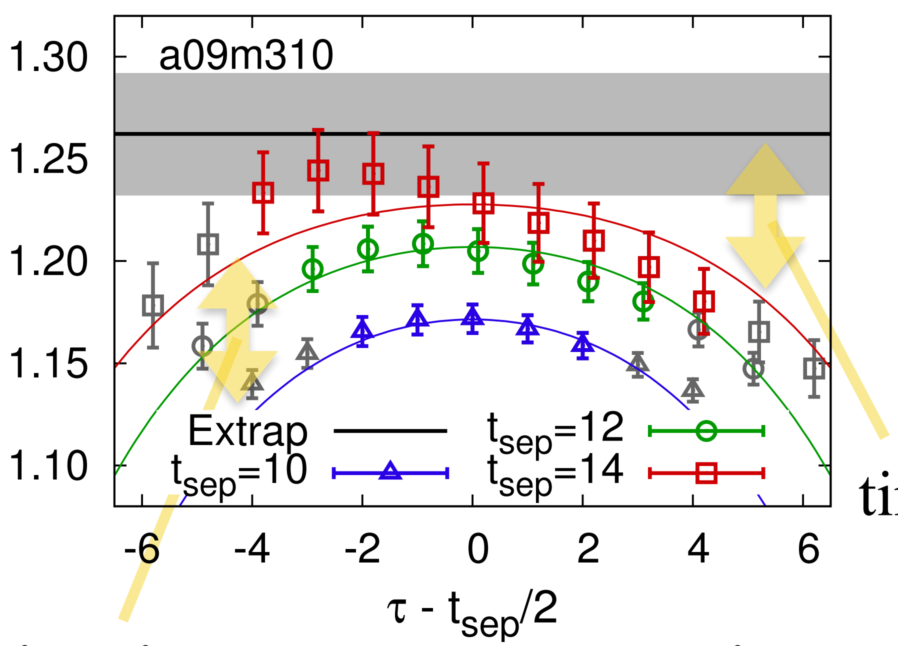
Nucleon Matrix Elements & Fundamental Symmetries

- Low energy precision tests of the Standard Model place competitive bounds on physics beyond the Standard Model (BSM) as compared to the LHC.
- Interpreting null results/hopeful signals in terms of potential BSM physics requires a quantitative and often precise knowledge of one- and sometimes two-nucleon matrix elements
  - direct dark matter detection
  - permanent electric dipole moments in nucleons and nuclei
  - modification from V-A weak beta decay, $n \to p + e^- + \bar{\nu}_e$
  - $\mu \to$ e conversion
  - …
- The largest uncertainty in many examples comes from the hadronic uncertainty of the nucleon matrix elements
- Lattice QCD calculations of nucleon matrix elements have one additional systematic that is more complicated than regular spectrum calculations: excited state systematics

Nucleon Matrix Elements & Fundamental Symmetries

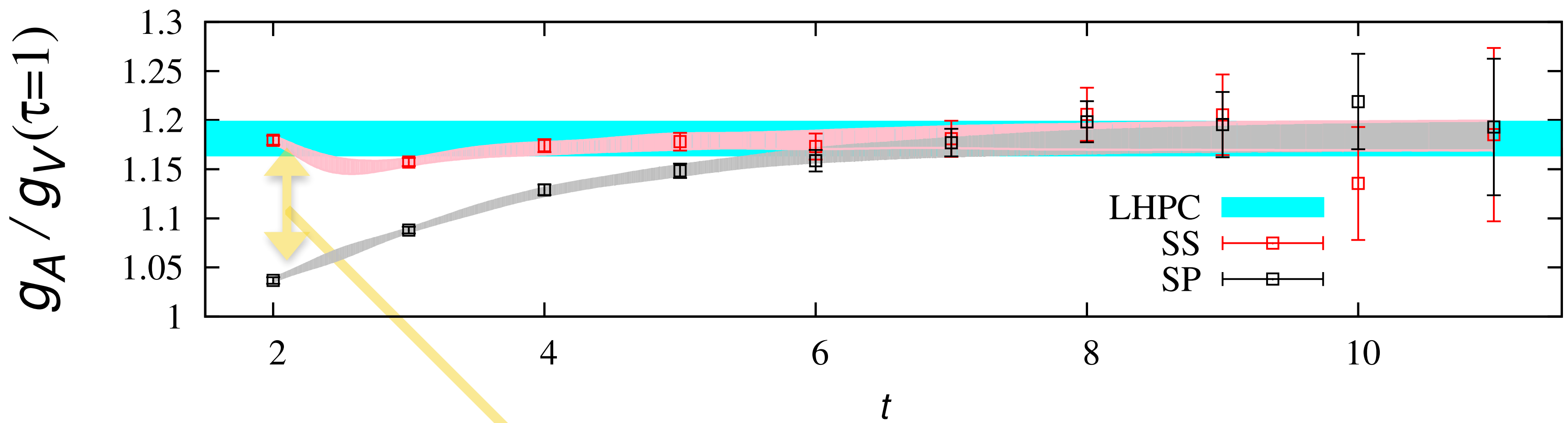
- With C. Bouchard, K. Orginos, we have developed a new method for computing matrix elements
  - significantly improved control over excited states systematics, based upon the Feynman-Hellman Theorem, in which all excited states contributions are **time-dependent** (controlled in fit to numerical results)
  - ~9 times more statistical results for approximately equal computing time
  - entire calculation is equivalent in cost to 1 single t_{sep} calculation of the standard approach

standard OLD method



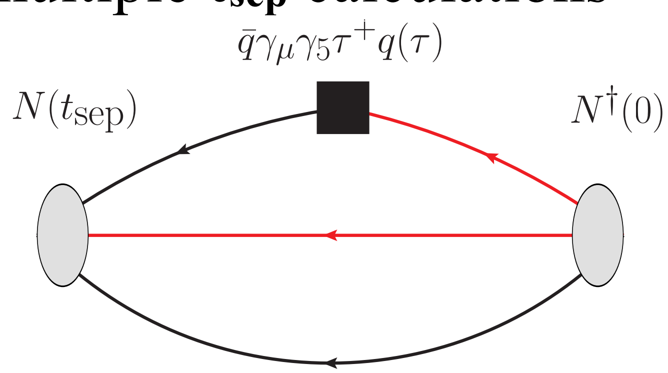
time-dependent systematics

NEW Feynman-Hellman method

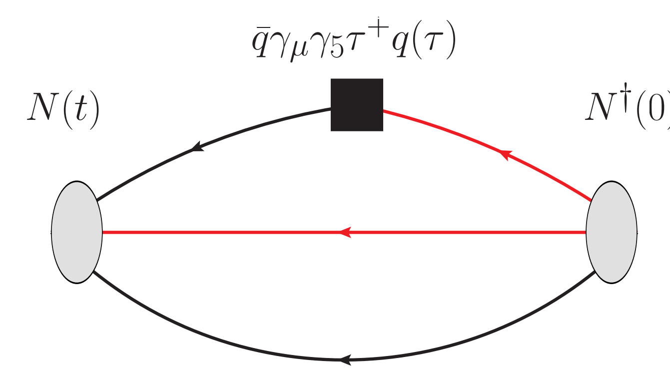


ONLY time-dependent systematics can fit with single calculation

time-independent systematics
need multiple **t_{sep}** calculations - expensive



$$\int d\tau$$



See poster by Chia Cheng (Jason) Chang

Embargoed Result

Lattice QCD for Nuclear Physics

1. Lattice QCD infrastructure: people and software
   a) we have a very active and tight-knit/engaged team of physicists and computer scientists
   b) we are developing independent software for our specialized needs

2. Hadronic Parity Violation (PV): I=2 NN PV Amplitude
   a) PV calculation on pause as we need to improve two-nucleon elastic scattering calculations
   b) we have developed an exciting new method that may provide exponential improvement in NN LQCD calculations - publication coming soon

3. Neutrinoless Double Beta-Decay ($0\nu\beta\beta$)
   a) $0\nu\beta\beta$ may receive important contributions from short-range 4-quark—2-electron operators (more general BSM theory causing Lepton-number violation)
   b) The term expected to dominate such a contribution comes from a short-range Isospin=2 pion matrix element $\pi^- \rightarrow \pi^+$
   c) We have nearly completed the calculation of this matrix element with LQCD - all that remains is the non-perturbative renormalization which we are performing now
   d) next is the calculation of two-nucleon operators - same technology as HPV

4. Nucleon Matrix Elements for Fundamental Symmetry Tests
   a) developed new method for computing matrix elements motivated by the Feynman-Hellman Theorem
   b) applied this new method to calculate the nucleon axial charge [redacted]